

# Efficient generation of universal two-dimensional cluster states with hybrid systems

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We present a scheme to generate two-dimensional cluster state efficiently. The number of the basic gate—entangler—for the operation is in the order of the entanglement bonds of a cluster state, and could be reduced greatly if one uses them repeatedly. The scheme is deterministic and uses few ancilla resources and no quantum memory. It is suitable for large-scale quantum computation and feasible with the current experimental technology.

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## I. INTRODUCTION

Measurement-based quantum computation (MBQC) or one-way quantum computation, which was firstly introduced by Briegel and Raussendorf [1], has been a hot topic in quantum information science recently. Different from the traditional circuit-based quantum computation implemented by single-qubit and multi-qubit gates, the necessary operation in MBQC is only projection measurement on single qubits. However, the resources for MBQC should be the entangled states of large numbers of qubits, which are conventionally called cluster state or graph state. The efficient generation of such entangled states is the main obstacle to the realization of MBQC. Many proposals have been put forward for creating cluster states in various physics systems. They include the discrete [2–4] and continuous variable [5] optical systems, the solid state systems such as charge qubits [7], flux qubit [8], quantum dot [9], etc.

Here we focus on the optical approaches to creating cluster states. In 2004, Nielsen proposed the method of adding photons one by one with controlled-Z (CZ) gates in generating a cluster state [2]. This scheme only uses linear optical elements, so it is probabilistic and the cost for creating a cluster state of large number of qubits could be very high. Later, many works were developed to generate cluster state more efficiently. One of them is the Browne-Rudolph protocol [3]. Two types of fusion gates are introduced in their protocol. The type-I fusion gate is used to connect two cluster state strings with a success probability  $1/2$ . After the operation of this gate, an undetected photon will be connected to the photon adjacent to a detected photon. The success of the gate is heralded by the detection of one photon, i.e. one photon must be sacrificed. On the other hand, by a type-II fusion gate, two photons are detected to create an L-shape cluster.

At least three photons must be consumed (one photon for the  $\sigma_x$  operation, and two photons for the Type-II fusion gate) in a complete operation. The Browne-Rudolph protocol only applies linear optics, but it is also non-deterministic and requires large quantity of sources (single photons), so it is not appropriate for large-scale quantum computation.

More recently, another approach to generating cluster states with weak nonlinearities were developed by S. G. R. Louis *et al.* [10]. With the  $\hat{X}$ -quadrature measurements, its cluster state generation could be deterministic, but the necessary amplitude of the measured coherent beams should be  $\alpha\theta^2 \gg 1$  ( $|\alpha|$  is the amplitude of the input coherent state, and  $\theta$  the cross phase shift), so giant nonlinearities should be demanded. If one chooses the  $\hat{P}$ -quadrature measurements, the scaling will reduce to  $\alpha\theta \gg 1$ , but it is non-deterministic with a success probability  $1/2$ . Moreover, their schemes require a minus cross phase shift  $-\theta$ , which is impractical [11].

Besides the theoretical proposals, MBQC were experimentally demonstrated with optical systems [12, 13], but it is impossible to follow these proof-of-principle experiments to perform the realistic MBQC because quantum memories are also necessary for storing the photonic cluster states. One could generate cluster state with probabilistic gate, e.g., probabilistic controlled phase flip gate [14], but it takes time to succeed in generating a whole cluster state by the repeated gate operations. The already generated part of the cluster state should be stored in quantum memories. If the efficiency of generation is not high enough, a large number of photonic qubits in the cluster state have to be kept in quantum memory for long time. Unfortunately, efficient and faithful quantum memories for photonic qubits are still under development thus far. Therefore, it is interesting to study how to quickly create photonic cluster states without quantum memory.

In this paper, we propose a scheme to generate 2D cluster state with hybrid systems involving discrete qubits and continuous variable states. This is a deterministic approach to generating photonic cluster state of large size. With the high efficiency of the scheme, only tem-

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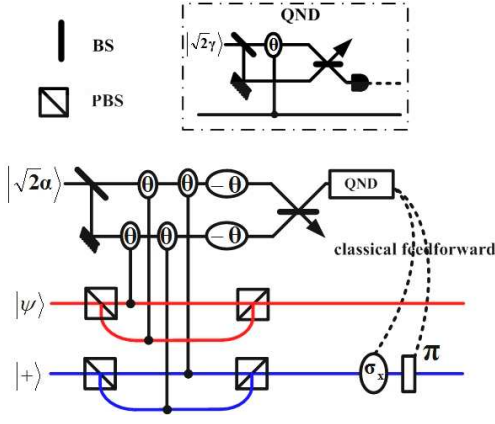


FIG. 1: (Color online) Schematic setup for entangler. Two qubus beams are coupled to the two single photons as indicated. The XPM phases  $\theta$  and two phase shifters  $-\theta$  are applied to the qubus beams. The QND module and the classical feedforward are used to make this operation to be deterministic. After that, an entangled state will be achieved.

porary storage such as delay lines would be necessary for the involved operations.

The rest of the work is organized as follows. First, we describe a hybrid system called entangler as the tool for creating the links of a cluster state. Then, in Sec. III and IV, we outline the procedures to generate a string cluster state and two types of box cluster state, respectively. Next, we present the main results about the generation of 2D cluster state in Sec. V. Finally we conclude the work with some discussions.

## II. BASIC TOOL—ENTANGLER

Before we present the scheme for generating cluster state, we describe the tool of us to create the entanglement links in a cluster state. This gate is called entangler briefly. It was first introduced by Pittman *et al.*, and then used to construct a CNOT gate [15]. Later, Nemoto *et al.* applied cross phase modulation (XPM) to make this gate deterministic [16]. Considering the impossibility of minus XPM phase shift  $-\theta$  in the scheme of [16], we used the technique of double XPM to make such operation feasible with XPM [17]. The schematic setup of our entangler is shown in Fig.1. The effect of the entangler is to map the product of the states  $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$  and  $|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$  as follows:

$$|\psi\rangle|+\rangle \xrightarrow{E} \alpha|0\rangle|0\rangle + \beta|1\rangle|1\rangle, \quad (1)$$

where  $E$  denotes the entangler operation. The two input states will be thus entangled, and the entangled output state inherits the coefficients of the input  $|\psi\rangle$ . As shown in [17], the error probability in the operation is

$$P_E \sim \exp\{-2(1 - e^{-\frac{1}{2}\eta\gamma^2\theta^2})\alpha^2 \sin^2 \theta\}, \quad (2)$$

where  $\alpha, \gamma$  are the amplitude of the coherent states used in the operation and quantum non-demolition (QND) module for number-resolving detection, respectively. Here  $\theta$  is the XPM phase shift, while  $\eta$  is the efficiency of the detector. Even if  $\theta \ll 1$  for a weak cross-Kerr nonlinearity, the operation would be deterministic given  $|\alpha| \sin \theta \gg 1$  and  $\eta\gamma^2\theta^2 \gg 1$ . It improves on the efficiency and feasibility of the entangler proposed in Refs. [10]. Moreover, the QND module could be implemented with photon number non-resolving detectors, such as APDs [17].

Using two entanglers and one ancilla photon, a deterministic CNOT gate or CZ gate can be realized [15, 16]. Alternatively, one can also use a pair of so-called C-path and Merging gate together with a recyclable ancilla photon to realize the gates [17, 18].

## III. GENERATION OF STRING CLUSTER STATE BY ENTANGLER

As we know, a cluster string can be generated using CZ gates one by one [1, 2, 19]. However, this way may not be efficient. In fact, using only one entangler is enough for generating a cluster string. We begin with two initial states  $|+\rangle, |+\rangle$ . If a CZ gate is implied on these two states, we will get the state  $\frac{1}{\sqrt{2}}(|0\rangle|+\rangle + |1\rangle|-\rangle)$ , which is a two-qubit cluster state. Since the target state is a special single photon state  $|+\rangle$ , just one entangler could let us to achieve the two-qubit cluster state. The processes can be described as follows,

$$\begin{aligned} \frac{1}{\sqrt{2}}|+\rangle|+\rangle &\xrightarrow{E} \frac{1}{\sqrt{2}}(|0\rangle|0\rangle + |1\rangle|1\rangle) \\ &\xrightarrow{H_2} \frac{1}{\sqrt{2}}(|0\rangle|+\rangle + |1\rangle|-\rangle), \end{aligned} \quad (3)$$

where  $H_2$  denotes the Hadamard gate performed only on the second photon. Using only one entangler and one Hadamard gate, we can obtain a two-qubit cluster state.

This method can be also used to add one photon to an already generated cluster state, as shown in part (3) of Fig. 2. In general, an already existing cluster state can be described in the unnormalized form  $|\Phi_1\rangle|0\rangle_p + |\Phi_2\rangle|1\rangle_p$ , where the other photons except the  $p$ -th photon could be in an arbitrary state  $|\Phi_{1(2)}\rangle$ . Now the process of adding one photon  $q$  in the state  $|+\rangle$  to the already prepared cluster state is as follows,

$$\begin{aligned} &(|\Phi_1\rangle|0\rangle_p + |\Phi_2\rangle|1\rangle_p)|+\rangle_q \\ &\xrightarrow{E_{pq}} |\Phi_1\rangle|0\rangle_p|0\rangle_q + |\Phi_2\rangle|1\rangle_p|1\rangle_q \\ &\xrightarrow{H_q} |\Phi_1\rangle|0\rangle_p|+\rangle_q + |\Phi_2\rangle|1\rangle_p|-\rangle_q. \end{aligned} \quad (4)$$

The final result is the target cluster state.

Using this technique, one can easily generate any cluster state strings as shown in part (1) of Fig. 2, and the

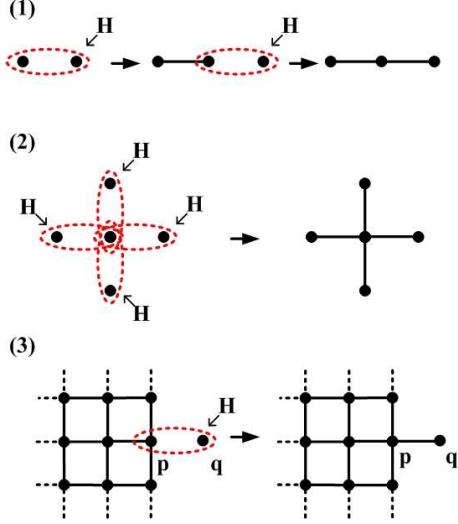


FIG. 2: (Color online) The generation of a cluster state string with entanglers. (1) Using entanglers and Hadamard operations to generate a cluster state string. (2) Using four entanglers and Hadamard operations to create a star cluster state. (3) using one entangler and Hadamard operation to add one photon to the already created cluster state.

star cluster state shown in part (2) of Fig. 2. In addition, one can only use entanglers to generate an alveolate graph shape deterministically (the projector of the PBS in Ref. [20] is actually an entangler) and a cluster state string simultaneously like the scheme in [21]. Another advantage is that no ancilla single photon is necessary in the operation of entanglers. By the way, it should be noted that, if one wants to connect two photons in two different already created cluster states, one CZ gate, or two entanglers plus one ancilla single photon equivalently, will be needed.

#### IV. GENERATION OF TWO-DIMENSIONAL BOX CLUSTER STATE BY ENTANGLER

A cluster state for practical MBQC should be of two-dimension (2D) structure. Of course, one could use CZ gates to connect cluster state strings to obtain a general 2D cluster state. However such practice could be still not efficient enough. In what follows, we will first show how to generate a box cluster state using a few entanglers, and then use the box cluster states as the basic elements to construct a general 2D cluster state in an efficient way.

##### A. Type-I box

The first scheme to generate a box cluster state is shown in part (1) of Fig. 3. At the beginning, we use two entanglers to generate a cluster state string of three

photons, which is described by the following state,

$$\frac{1}{2} (|0\rangle|+\rangle|0\rangle + |0\rangle|-\rangle|1\rangle + |1\rangle|-\rangle|0\rangle + |1\rangle|+\rangle|1\rangle)_{123}. \quad (5)$$

Then, performing a Hadamard operation on the second photon, we will get

$$\frac{1}{2} (|0\rangle|0\rangle|0\rangle + |0\rangle|1\rangle|1\rangle + |1\rangle|1\rangle|0\rangle + |1\rangle|0\rangle|1\rangle)_{123}. \quad (6)$$

Next, applying an entangler operation on photon 2 and the photon 4 (initially in the state  $|+\rangle$ ) yields the state

$$\begin{aligned} & \frac{1}{2} (|0\rangle|0\rangle|0\rangle|0\rangle + |0\rangle|1\rangle|1\rangle|1\rangle \\ & + |1\rangle|1\rangle|0\rangle|1\rangle + |1\rangle|0\rangle|1\rangle|0\rangle)_{1234}. \end{aligned} \quad (7)$$

Finally, a Hadamard operation is performed on the second and fourth photon, respectively, and we will obtain the following state:

$$\begin{aligned} & \frac{1}{2} (|0\rangle|+\rangle|0\rangle|+\rangle + |0\rangle|-\rangle|1\rangle|-\rangle \\ & + |1\rangle|-\rangle|0\rangle|-\rangle + |1\rangle|+\rangle|1\rangle|+\rangle)_{1234}, \end{aligned} \quad (8)$$

which is a box cluster state [12]. In this process, we generate two bonds ( $4 \rightarrow 1, 4 \rightarrow 3$ ) simply by one entangler operation and three Hadamard operations. The reason why the operation could be thus simplified with entangler operation is that the box cluster state has a perfect symmetry. Seen from photon 1 or 3, photon 2 and 4 are symmetric, so the states of them are equivalent and one entangler operation will be enough for connecting both bonds. Totally, 3 entangler operations, not 4 CZ gates, will be necessary to generate a box cluster state. No ancilla photon is needed for the entangler operations here.

Generalizing the scheme to adding a box cluster state to an already generated cluster state is straightforward. The schematic setups are shown in part (2) of Fig. 3. Generally, an already created cluster state is in the unnormalized form  $|\Phi_1\rangle|0\rangle_p + |\Phi_2\rangle|1\rangle_p$ . First we apply the procedure in Eq. (3) to add one photon ( $|+\rangle_q$ ) to an already created cluster state to get the state  $|\Phi_1\rangle|0\rangle_p|+\rangle_q + |\Phi_2\rangle|1\rangle_p|-\rangle_q$ . Secondly, continuing to add one more photon ( $|+\rangle_r$ ) to obtain the state

$$\begin{aligned} & \frac{1}{\sqrt{2}} \left[ |\Phi_1\rangle|0\rangle_p \left( |0\rangle_q|+\rangle_r + |1\rangle_q|-\rangle_r \right) \right. \\ & \left. + |\Phi_2\rangle|1\rangle_p \left( |0\rangle_q|+\rangle_r - |1\rangle_q|-\rangle_r \right) \right] \\ & = \frac{1}{\sqrt{2}} \left[ |\Phi_1\rangle|0\rangle_p \left( |+\rangle_q|0\rangle_r + |-\rangle_q|1\rangle_r \right) \right. \\ & \left. + |\Phi_2\rangle|1\rangle_p \left( |-\rangle_q|0\rangle_r + |+\rangle_q|1\rangle_r \right) \right]. \end{aligned} \quad (9)$$

Finally, by a similar process shown from Eq. (5) to Eq.

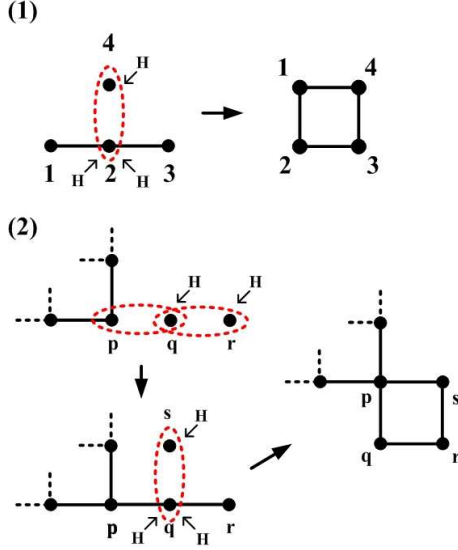


FIG. 3: (Color online) Schematic setup for generating Type-I box. (1) One entangler plus three Hadamard operations are performed on photon 2 and 4 in order to connect two links, 1-4, 3-4. Then a box cluster state could be generated by only three entangler operation without ancilla photon. (3) The generalization of adding a box structure to an already generated cluster state.

(8), we can achieve the following state

$$\begin{aligned} & \frac{1}{\sqrt{2}} |\Phi_1\rangle (|0\rangle |+\rangle |0\rangle |+\rangle + |0\rangle |-\rangle |1\rangle |-\rangle)_{pqrs} \\ & + \frac{1}{\sqrt{2}} |\Phi_2\rangle (|1\rangle |-\rangle |0\rangle |-\rangle + |1\rangle |+\rangle |1\rangle |+\rangle)_{pqrs}, \end{aligned} \quad (10)$$

which is the desired cluster state. With only 3 entanglers, we can add a box structure to an already created cluster state. Here only one photon in the added box belongs to the already created cluster state, i.e., the added box must include three photons which are not in the already generated cluster states. We call this type of box cluster state as Type-I box.

### B. Type-II box

Since the type-I box can only be used to add three photons to an already generated cluster state, its application in generating a 2D cluster state is limited. Here we introduce another type of box cluster state called Type-II box (Fig.4). This box could be used to connect two photons which belong to an already created cluster states (or two different cluster states) and two independent photons. Suppose the already generated cluster state is initially prepared as (unnormalized)

$$\begin{aligned} & |\Psi_1\rangle |0\rangle_p |0\rangle_s + |\Psi_2\rangle |0\rangle_p |1\rangle_s \\ & + |\Psi_3\rangle |1\rangle_p |0\rangle_s + |\Psi_4\rangle |1\rangle_p |1\rangle_s. \end{aligned} \quad (11)$$

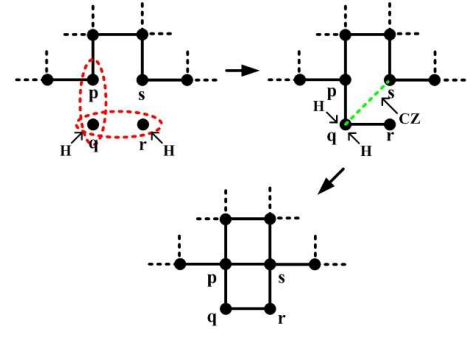


FIG. 4: (Color online) Schematic setup for generating Type-II box. Two entanglers are used to add two single photons to the already generated cluster state. Then, one CZ operation is performed on photon q and s for creating two links, s-r, s-p. Totally, four entanglers with one ancilla photon are required to add a Type-II box between two already created cluster states.

At first, we use two entanglers and some Hadamard operations to add two photons respectively in the states  $|+\rangle_q, |+\rangle_r$  to the above cluster state to get the following state

$$\begin{aligned} & \frac{1}{\sqrt{2}} \left[ |\Psi_1\rangle |0\rangle_p |0\rangle_s (|+\rangle_q |0\rangle_r + |-\rangle_q |1\rangle_r) \right. \\ & + |\Psi_2\rangle |0\rangle_p |1\rangle_s (|+\rangle_q |0\rangle_r + |-\rangle_q |1\rangle_r) \\ & + |\Psi_3\rangle |1\rangle_p |0\rangle_s (|-\rangle_q |0\rangle_r + |+\rangle_q |1\rangle_r) \\ & \left. + |\Psi_4\rangle |1\rangle_p |1\rangle_s (|-\rangle_q |0\rangle_r + |+\rangle_q |1\rangle_r) \right]. \end{aligned} \quad (12)$$

Next, after a Hadamard operation is performed on photon q, we perform a CZ operation on photon q and s, respectively. Finally, a Hadamard operation on photon q will achieve the state

$$\begin{aligned} & \frac{1}{\sqrt{2}} \left[ |\Psi_1\rangle |0\rangle_p |0\rangle_s (|+\rangle_q |0\rangle_r + |-\rangle_q |1\rangle_r) \right. \\ & + |\Psi_2\rangle |0\rangle_p |1\rangle_s (|+\rangle_q |0\rangle_r - |-\rangle_q |1\rangle_r) \\ & + |\Psi_3\rangle |1\rangle_p |0\rangle_s (|-\rangle_q |0\rangle_r + |+\rangle_q |1\rangle_r) \\ & \left. + |\Psi_4\rangle |1\rangle_p |1\rangle_s (-|-\rangle_q |0\rangle_r + |+\rangle_q |1\rangle_r) \right]. \end{aligned} \quad (13)$$

which is the target cluster state with the box structure for the photons p, q, r, s. Two entangler operations and one CZ gate are necessary for generating this Type-II box. Since a CZ gate could be implemented by two entanglers, four entanglers will be enough to create this type of box. On average, one entanglement bond needs one entangler operation by this method.

## V. CREATING A GENERAL 2-D CLUSTER STATE WITH ENTANGLERS AND CZ GATES

In a classical computer, a simple computation task could involve thousands of bits. Though numerous experiments in MBQC have shown the power of quantum computation, all of them are proof of principle in nature [12, 13]. The quantities of qubits in these experiments are limited, and only simple operations could be demonstrated. Highly efficient schemes of generating cluster states must be developed before the large-scale computation in MBQC could possibly materialize. As the main topic of the paper, we will show in the following how to generate an arbitrary 2D cluster state using the above discussed string, box cluster states as the basic elements.

We illustrate the procedure with the example of a  $5 \times 5$  cluster state, which is shown in Fig. 5. Six steps will complete the generation of this cluster state:

- (1) using 8 entangler operations, a cluster state string of 9 qubits is generated;
- (2) applying the procedure of creating Type-I box for four times, a cluster state of four boxes will be achieved;
- (3) adding two cluster state strings of 4 qubits to the second box, and then two Type-I box will be added to the four-box cluster state with two entanglers;
- (4) continuing to add two type-II box to the six-box cluster state with two cluster state strings and two CZ gates;
- (5) adding two independent photons to the eight-box cluster state with two entanglers;
- (6) finally, six CZ gates will connect the links to the target  $5 \times 5$  cluster state.

Here we neglect the use of Hadamard operations for a simpler illustration. Now, we calculate the resources required in this scheme. Besides some single-qubit operations, 24 entanglers are required in the generation of string, two types of box structures; 8 CZ gates are required in the generation of Type-II box and in the final step. Considering the fact that one CZ gate could be realized by two entanglers, totally 40 entanglers should be used in this scheme. The number of entanglers is exactly equal to the bonds of the  $5 \times 5$  cluster state.

It is straightforward to generalize this method to create an  $n \times n$  cluster state in the approach. If  $n$  is odd,  $n^2 - 1$  entanglers and  $(n - 1)^2 / 2$  CZ gates, or totally  $2n(n - 1)$  entanglers will be required in the generation of a  $n \times n$  cluster state. If  $n$  is even,  $n^2 - 1$  entanglers and  $n(n - 2) / 2$  CZ gates, or totally  $2n(n - 1) - 1$  entanglers will be necessary to generate the cluster state. Evidently, the number of the entanglers is less than or equal to the number of the bonds. In other words, we could generate a universal 2D cluster state with one entangler operation per bond, so the scheme is highly efficient.

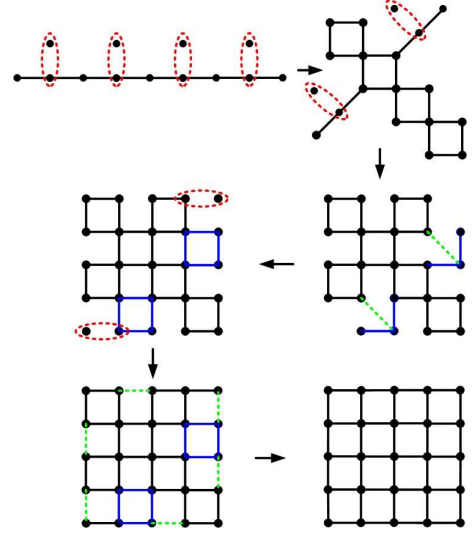


FIG. 5: (Color online) The generation of a  $5 \times 5$  cluster state from string and two types of box structures. A 9-photon cluster string and four entanglers are used to create four Type-I box cluster states, and then two Type-I boxes are added by six entanglers. Next, two Type-II boxes generated by four entanglers and two CZ gates will be used. After that, with two entanglers, two independent photons will be added to the eight-box cluster state. At the last step, six CZ gates are applied to complete the generation. There are totally 40 necessary entanglers. The number of entanglers is equal to that of the bonds of the cluster state.

## VI. DISCUSSION AND CONCLUSION

In this paper, we propose a scheme to generate a general 2D cluster state with entanglers plus a few CZ gates. In their realizations with linear optics and weak nonlinearity [17], entangler operations need no ancilla single photon and a CZ gate operation uses one ancilla photon which could be recycled if we use QND module in detection. It is also shown in [17] that QND module could be realized with common photon number non-resolving detectors such as APDs. Therefore, only one ancilla single photon is necessary for creating a general 2D cluster state in principle, even if the cluster state involves large number of qubits.

The number of the basic gate—entangler—required by the scheme is in the order of the cluster state bond number, and the resources will be greatly reduced if the entanglers are used repeatedly in operation. Actually, this scheme works with the fixed circuits (entanglers or CZ gates) with which the different links can be generated by the same setup if the process is in time order. Like the operations in a classical computer, only the simultaneous operations require different circuit resources, so the number of the necessary entanglers could be much smaller than the number of bonds in a cluster state. We indicate the time order with the arrows in figures, where the different steps could be done by the same entangler, CZ gate, etc. Moreover, the system enjoys the advantage

of deterministic operation of entanglers, and it reduces the generation time for clusters greatly. So the scheme is more suitable for large-scale quantum computation than the previously proposed ones.

As mentioned in the introduction, quantum memory is required in the schemes with probabilistic gates, which repeats the operation until success. The already generated parts should be stored in memory. However, the realization of high-quality quantum memory is still technically challenging. In our scheme, the entangler operation based on XPM is deterministic and very fast (the operation time is in the order of that for the signals going through the nonlinear medium). So the storage time for the already generated parts need not to be long, and one could use some temporary storage, such as delay lines, for the already created parts. In this sense, the scheme could

be feasible with the current experimental technology.

The scheme improves on the previous ones by replacing the "one by one" fashion of generating the entanglement links with the "string by string" and "box by box", which increase the efficiency greatly. In particular, this approach to MBQC is deterministic, and uses less resources and no quantum memory. It could be a promising candidate for large-scale quantum computation.

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